Terrestrial Planet Finder

TPF

Terrestrial Planet Finder Coronagraph

System Studies

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Jet Propulsion Laboratory, California Institute of Technology

REPRESENTING WORK OF TPF CORONAGRAPH SYSTEM TEAM

NORTHROP GRUMMAN Space Technology

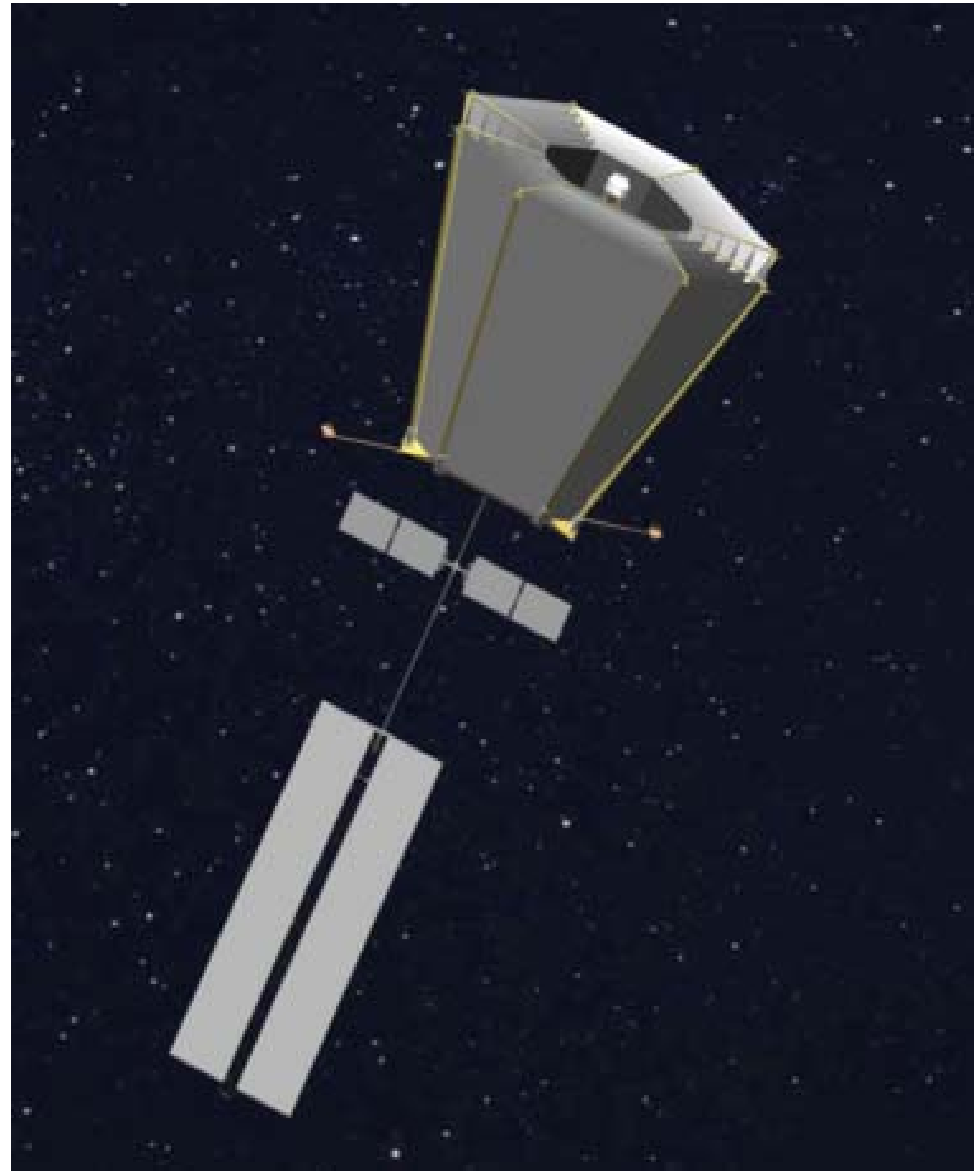
Ball Aerospace & Technologies Corp.

LOCKHEED MARTIN

TC Technology

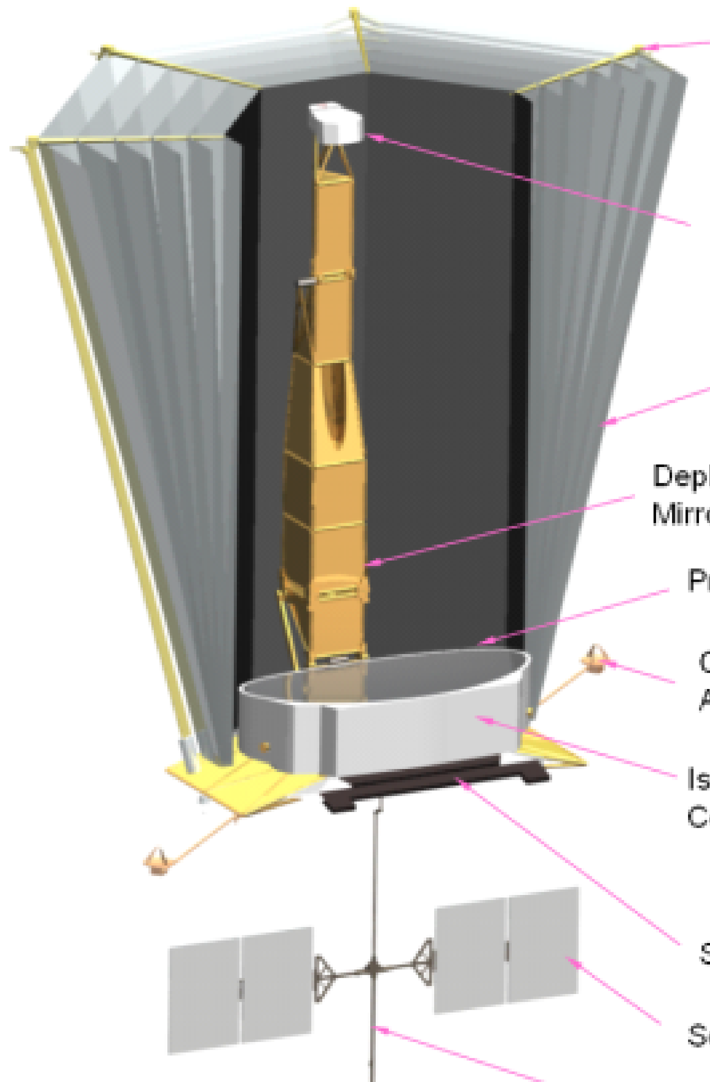
Goddard Space Flight Center

MIDE

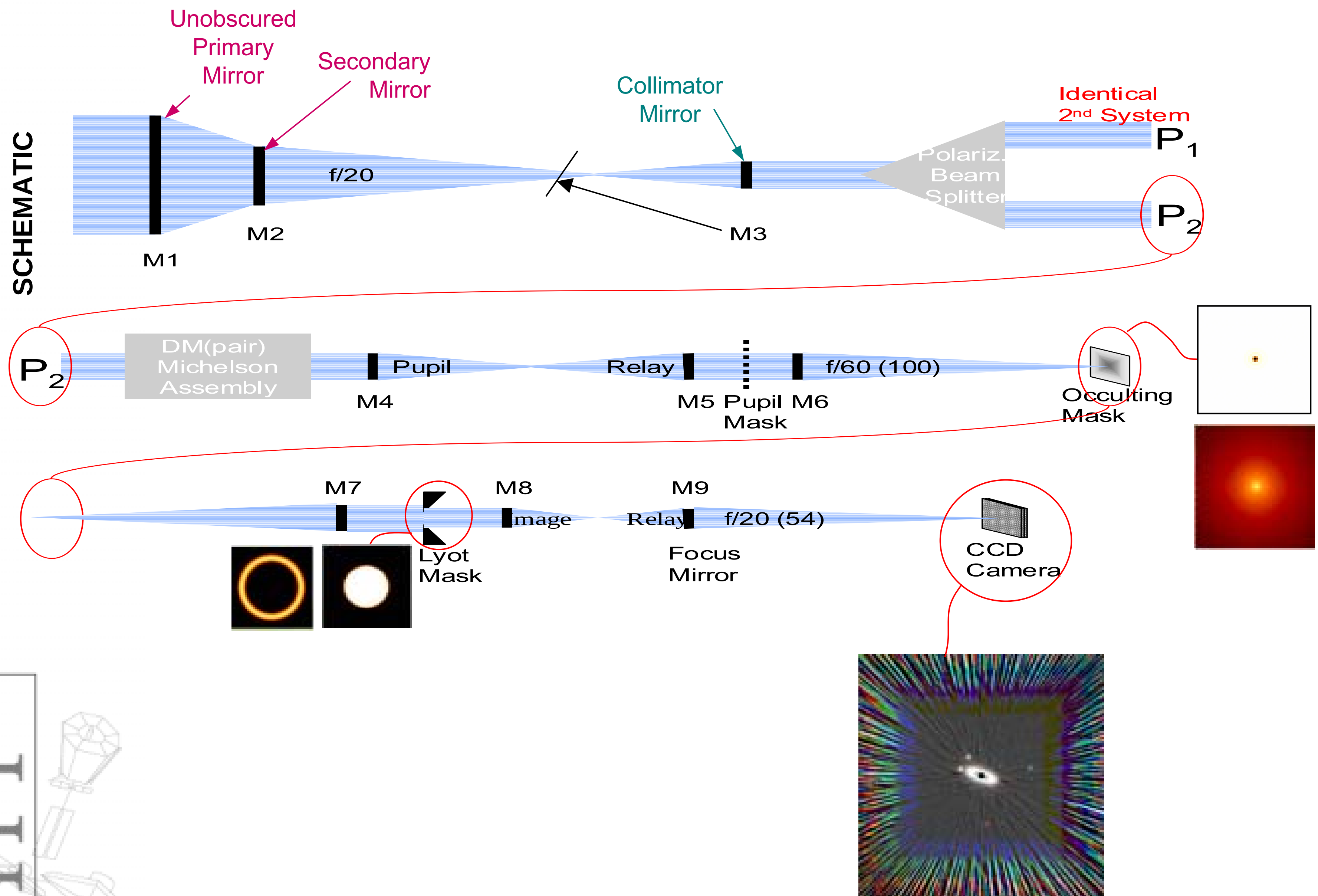


What I am going to cover

- Technology Development
- TPF Coronagraph mission concept
- Modeling and Analysis



TPF Coronagraph Optical Schematic



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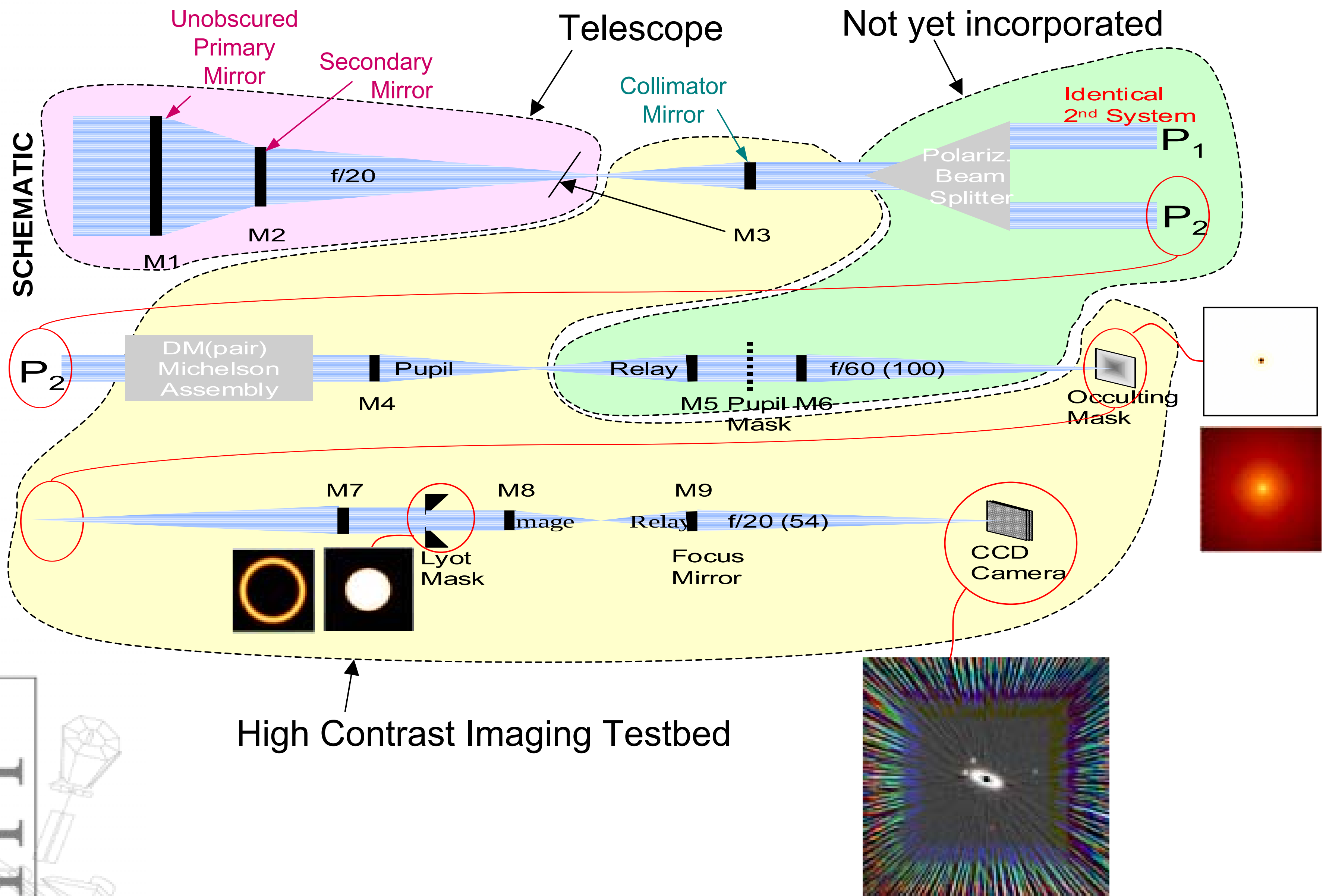
TPF Coronagraph Optical Schematic



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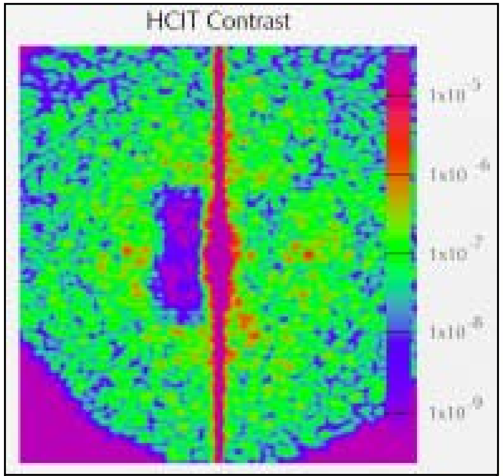
HCIT and new technology development

High Contrast Enabling Technology
Xinetics, Inc. Deformable Mirrors
in use in HCIT
Top: 64x64 actuator model
Bottom: 32x32 actuator model



Data by Trauger, Burrows & Moody, HCIT May 2004

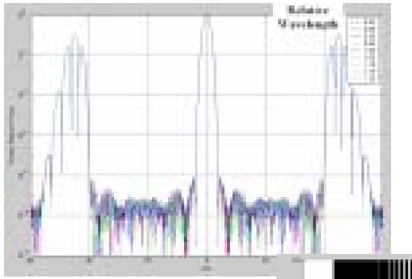
High Contrast Imaging Testbed
Remote Guest Testing in progress Contrast Results to date: 1.5x10e-9

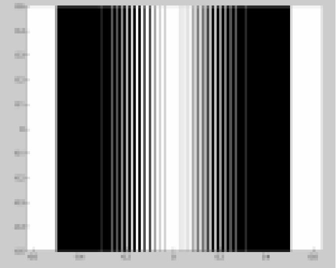
MEMS Deformable Mirrors under TPF development contract with Boston University

Mask Characterization Test Set

Figure 3. Photo of optical setup in dust-free enclosure.

Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace and Princeton





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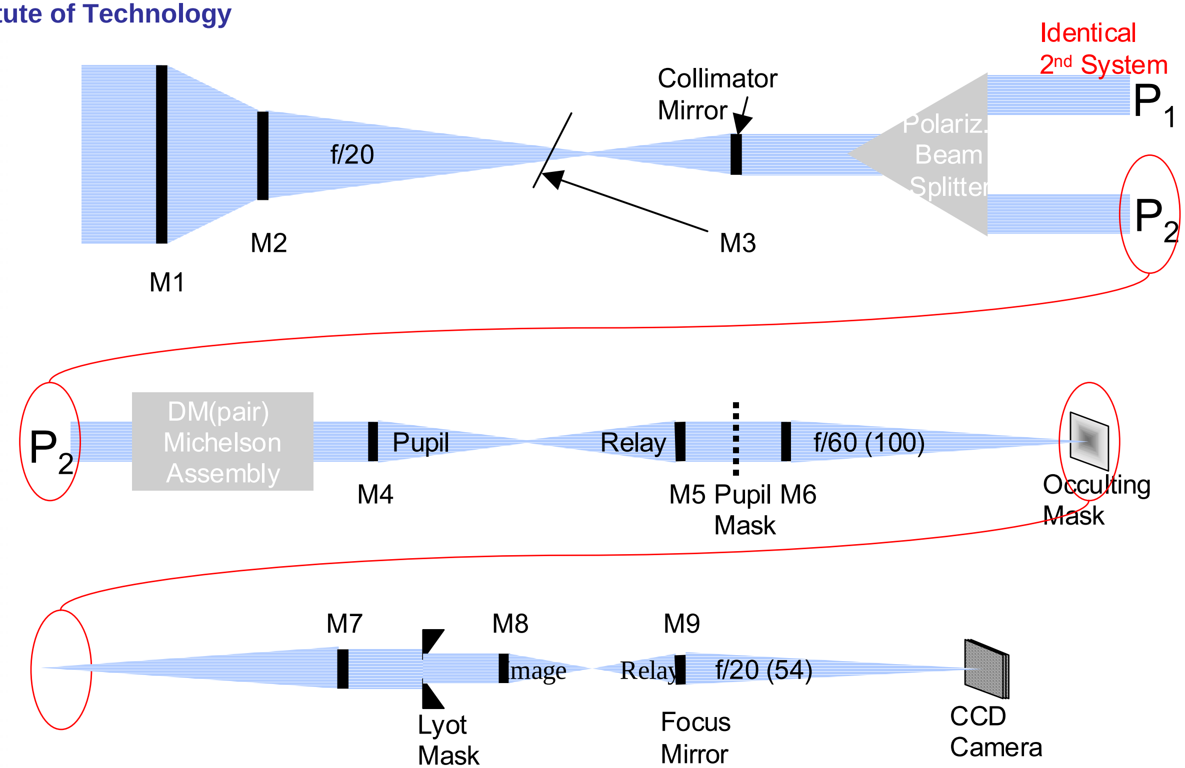
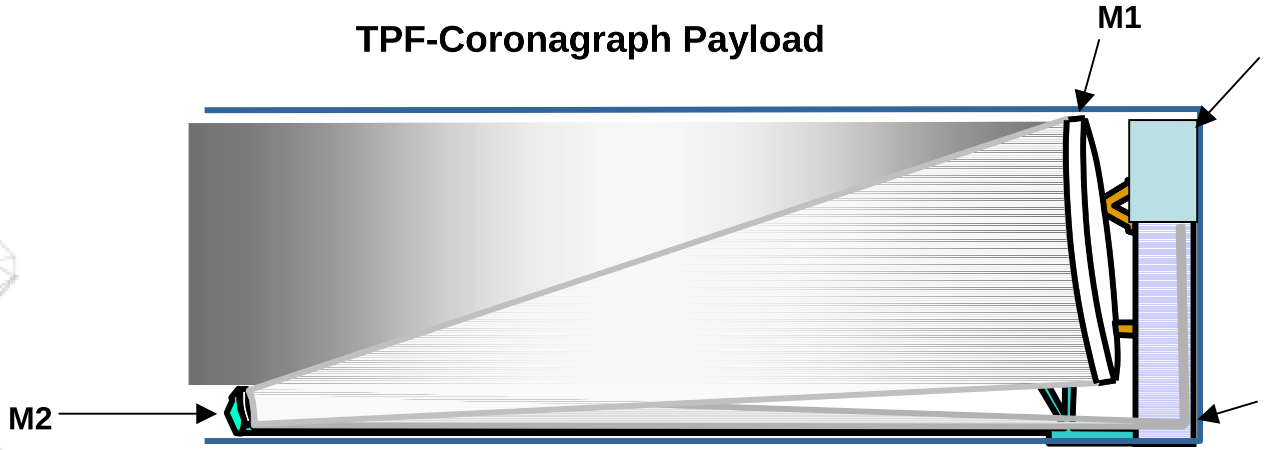
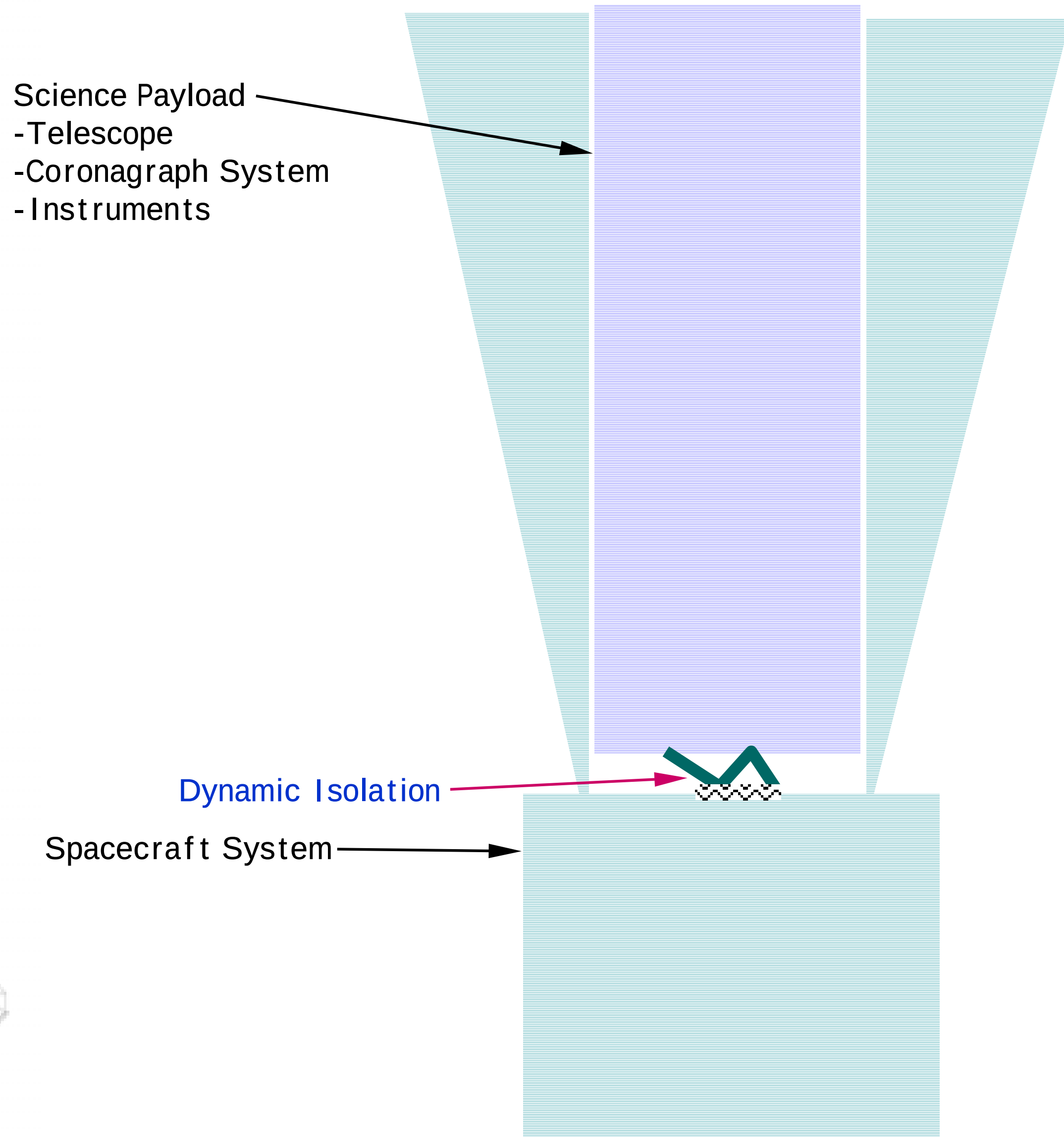
TPF Architecture Coronagraph Description



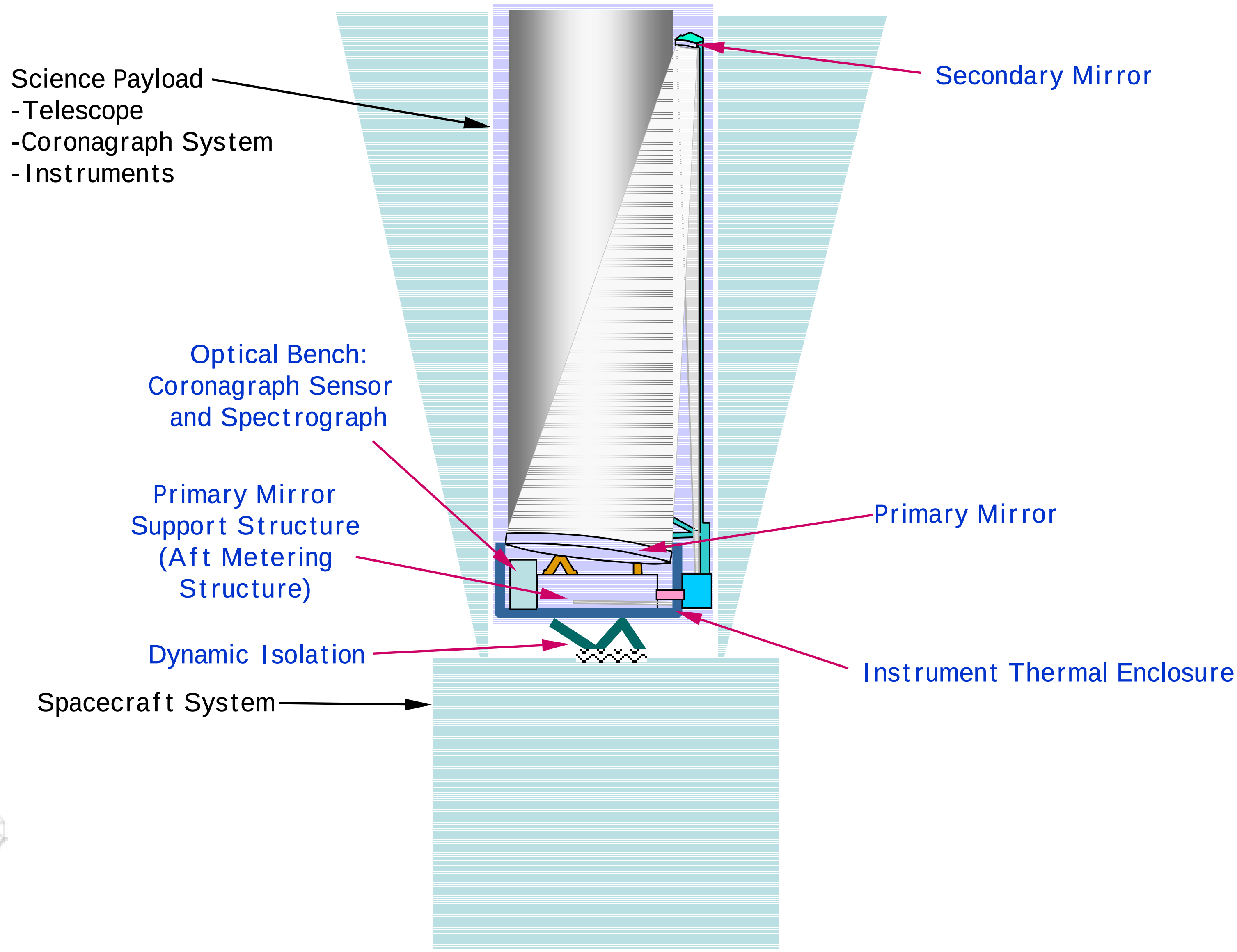
TPF-Coronagraph Payload



Configuration Schematic



Configuration Schematic



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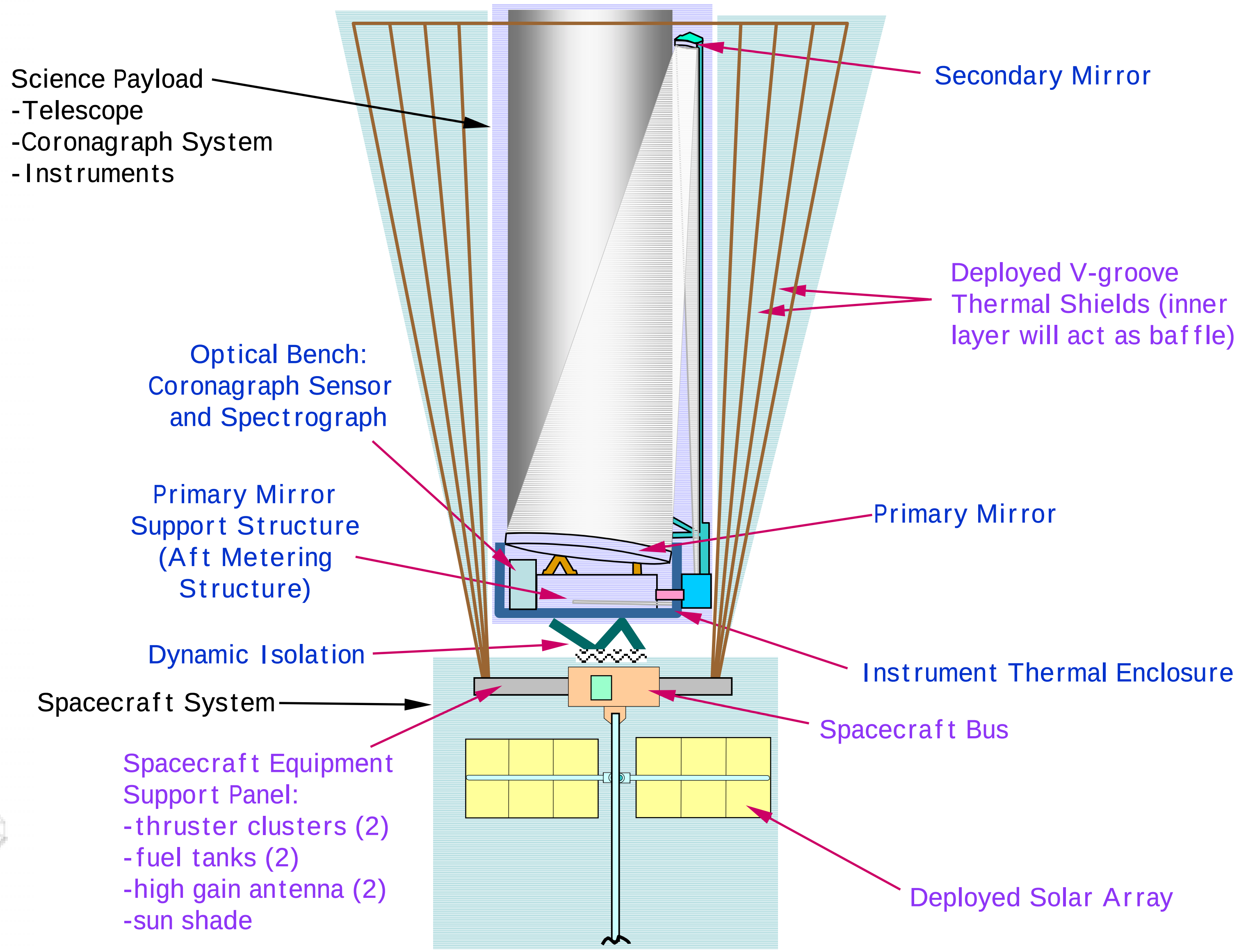
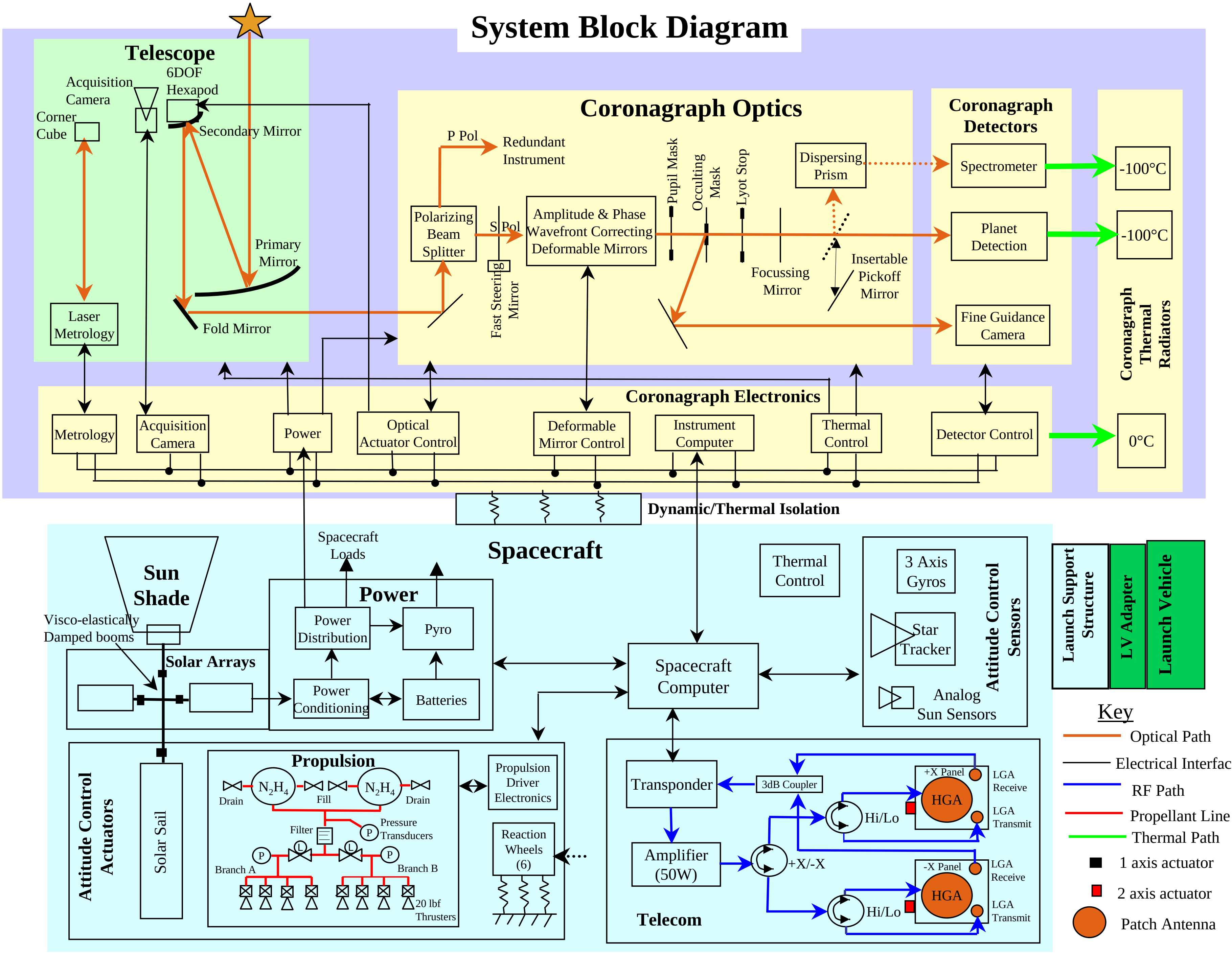
Configuration Schematic



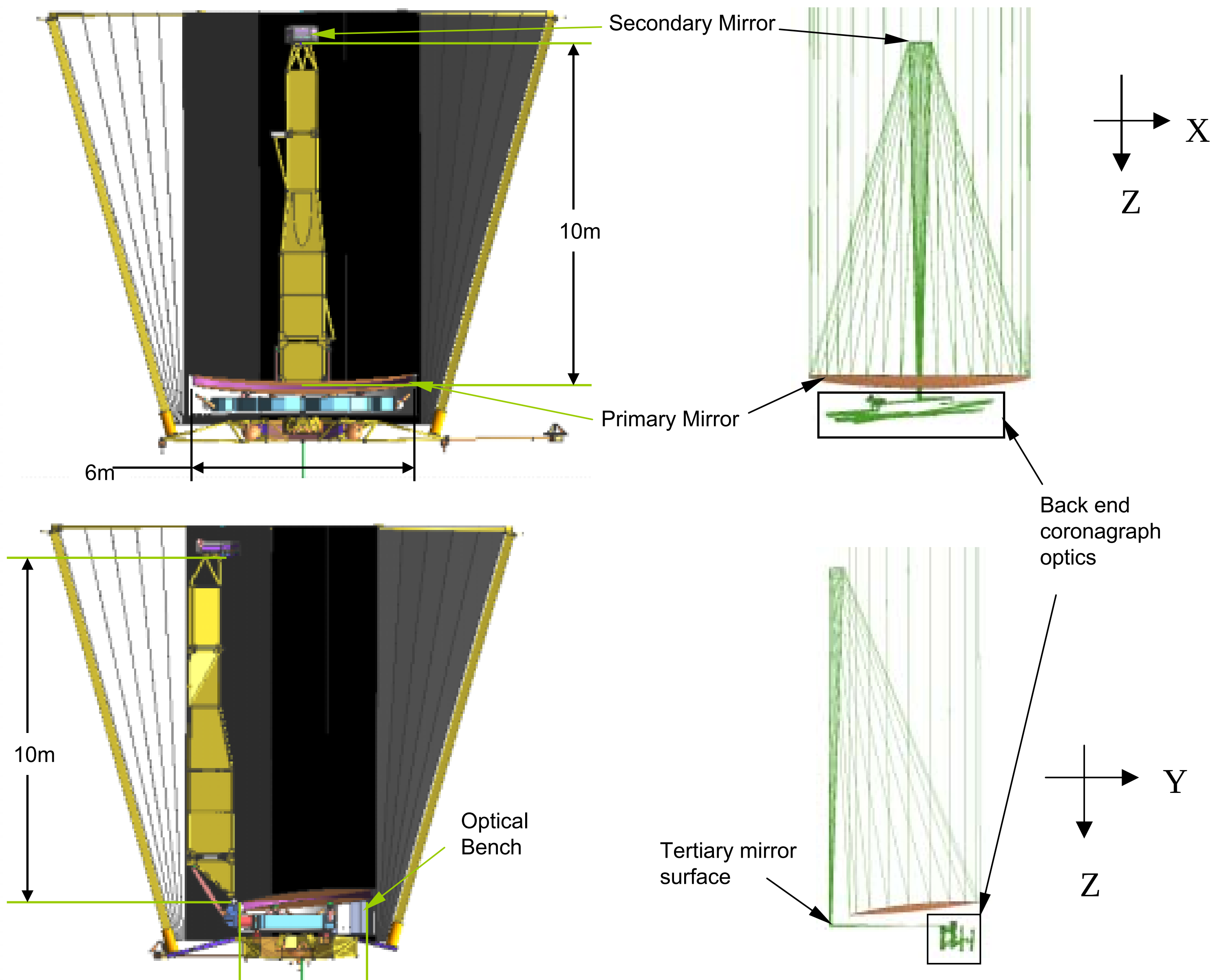
TPF Terrestrial Planet Finder


System Block Diagram
Telescope
Acquisition Camera
6DOF Hexapod
Corner Cube
Secondary Mirror
Primary Mirror
Laser Metrology
Fold Mirror
Coronagraph Optics
P Pol
Redundant Instrument
Polarizing Beam Splitter
S Pol
Fast Steering Mirror
Amplitude & Phase Wavefront Correcting Deformable Mirrors
Pupil Mask
Occulting Mask
Lyot Stop
Dispersing Prism
Focussing Mirror
Insertable Pickoff Mirror
Coronagraph Detectors
Spectrometer
Planet Detection
Fine Guidance Camera
-100°C
-100°C
0°C
Coronagraph Thermal Radiators
Coronagraph Electronics
Metrology
Acquisition Camera
Power
Optical Actuator Control
Deformable Mirror Control
Instrument Computer
Thermal Control
Detector Control
Dynamic/Thermal Isolation
Spacecraft
Sun Shade
Visco-elastically Damped booms
Solar Arrays
Spacecraft Loads
Power
Power Distribution
Pyro
Power Conditioning
Batteries
Thermal Control
3 Axis Gyros
Star Tracker
Analog Sun Sensors
Attitude Control Sensors
Spacecraft Computer
Launch Support Structure
LV Adapter
Launch Vehicle
Attitude Control Actuators
Solar Sail
Propulsion
Drain
Fill
Drain
Filter
Pressure Transducers
Branch A
Branch B
20 lbf Thrusters
Propulsion Driver Electronics
Reaction Wheels (6)
Transponder
3dB Coupler
Amplifier (50W)
+X/-X
Hi/Lo
Hi/Lo
+X Panel
-X Panel
HGA
HGA
LGA Receive
LGA Transmit
LGA Receive
LGA Transmit
Telecom
Key
Optical Path
RF Path
Propellant Line
Thermal Path
1 axis actuator
2 axis actuator
Patch Antenna

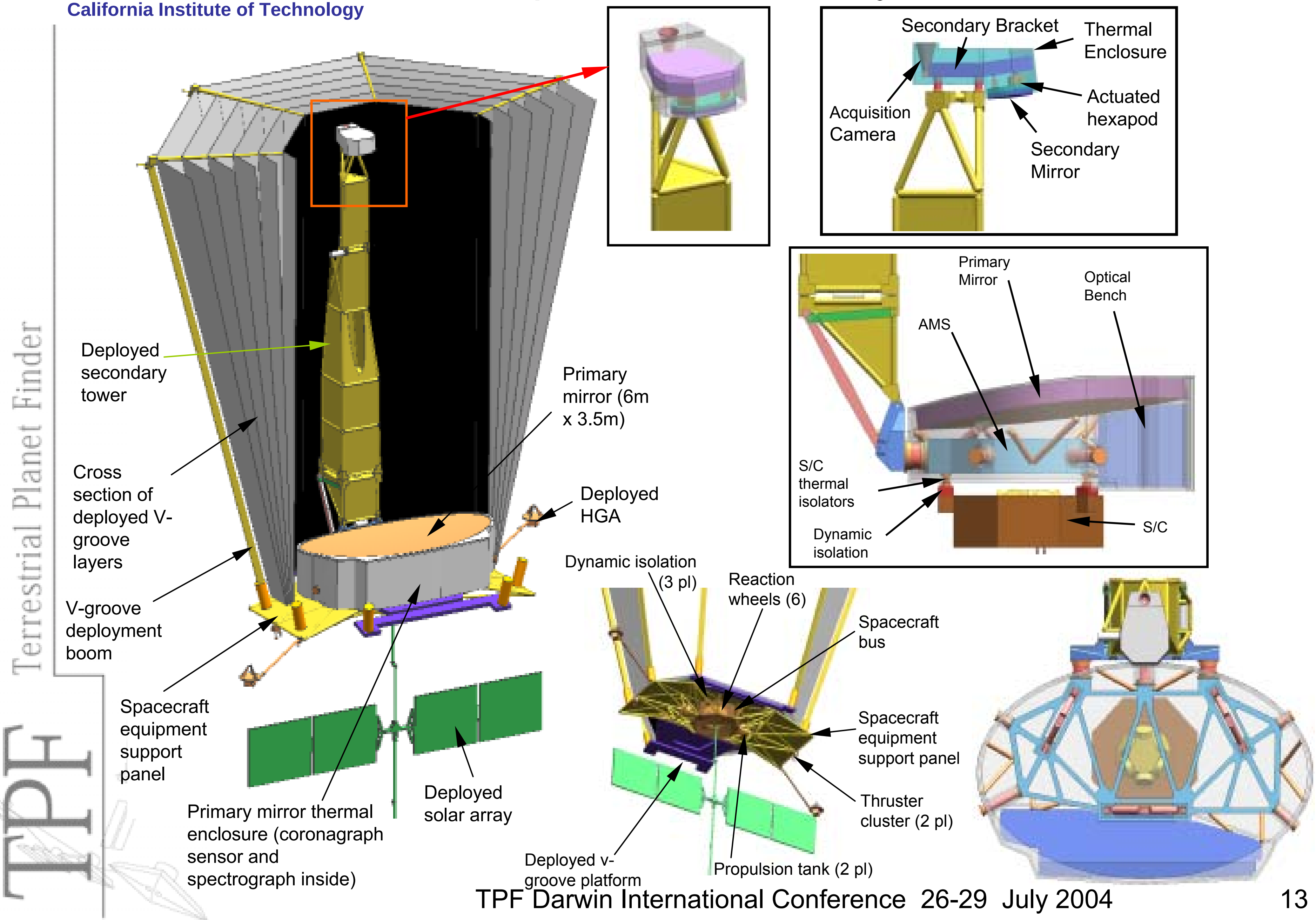
Systems Summary

- Mission Overview
  - 2014 Launch Date
  - Earth Drift-Away orbit (ala SIRTF)
    - 0.1AU/yr average earth separation rate
    - No cruise phase to operating orbit
  - Delta-IVH launch vehicle with 5m x 19m fairing
    - 10,000 kg lift capacity to C_3 of 0.4
  - 5 year primary mission duration with consumables for 10 years
    - 6 month post-launch checkout and calibration
    - Planet search phase spans 3 years
  - X-Band communications to 34m DSN
    - Continuous link capability & Hi Rate science downlink concurrent with data collection
    - Capability to downlink 3 days of stored data (~2Gb per day) in 1 8hr pass
- Systems Overview
  - Power: 3,000W solar array
  - Propulsion: 100kg Hydrazine in Blow-Down Mode
    - No ΔV required
    - Provide safe sun point and some momentum management (solar sail is prime)
  - Attitude Control: 3 axis stabilized
    - Star-trackers, gyros, sun sensors, plus instrument provided Acquisition Camera
    - 6 Reaction Wheels (Ithaco E Wheels)
    - Solar Sail with 1 axis articulation for balancing solar pressure torques
  - Telecommunications: 256 kbps science downlink
    - X-Band transponder
    - 50W amplifier
    - 2 30dB HGAs with 2 axis articulation
  - Thermal Control: V-Groove sun shade

Minimum Mission Configuration



Telescope and Secondary Mirror Assemblies



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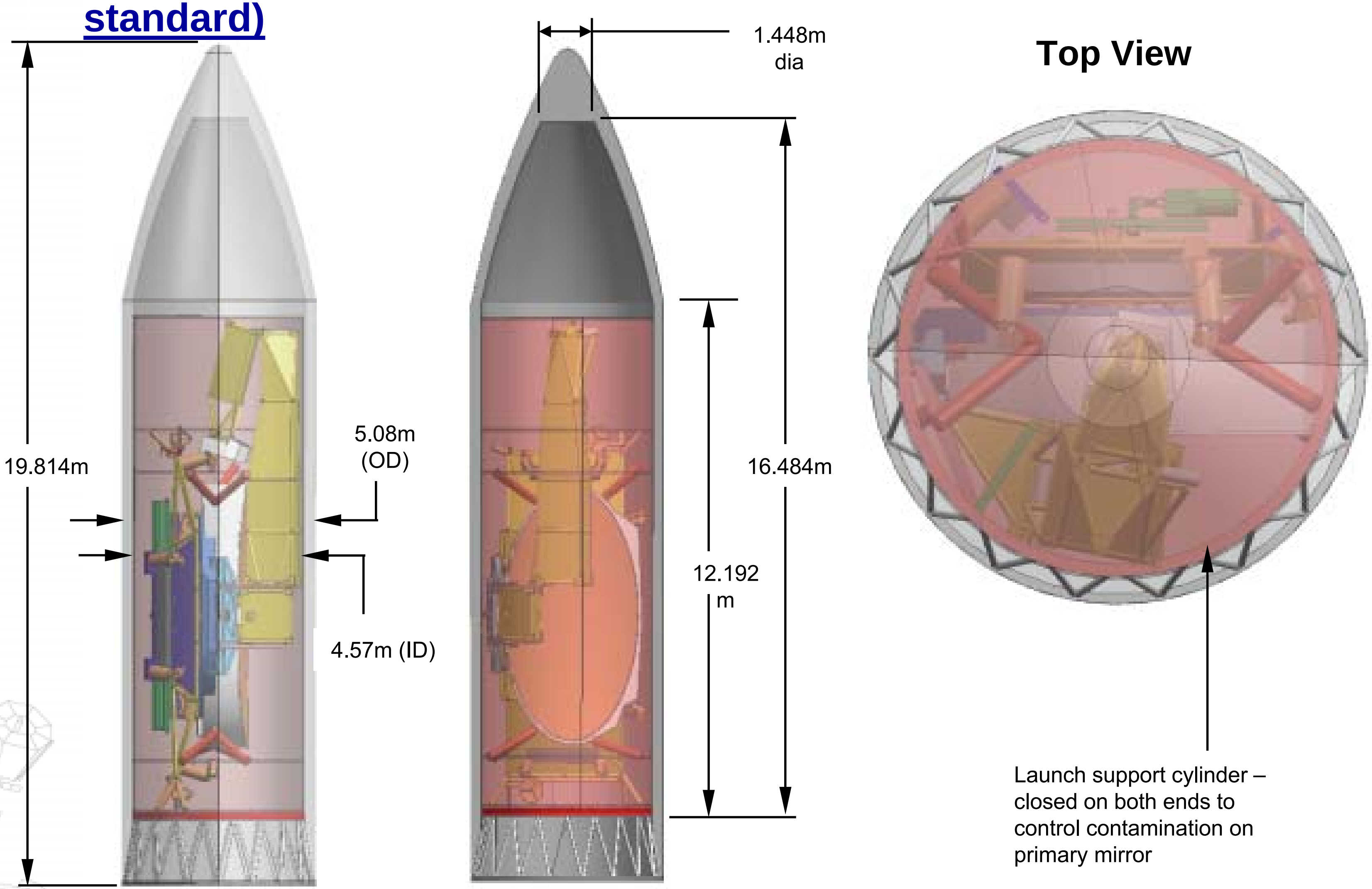
Stowed Mechanical Configuration

Stowed Configuration in Delta IV-H (19.8m gov't standard)



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Thermal Control Concept - Cocoon

- **Active control at ‘room’ temperature**

Entire telescope, optics bench and sensor maintained at room temperature by a precision control system

Rejected - required stability (< 10 mK) exceeds control system state-of-the-art

- **Hybrid semi-active/passive control**

Back of primary mirror, aft optics,optics bench and coronagraph contained in precision-controlled isothermal cavity ~300 K

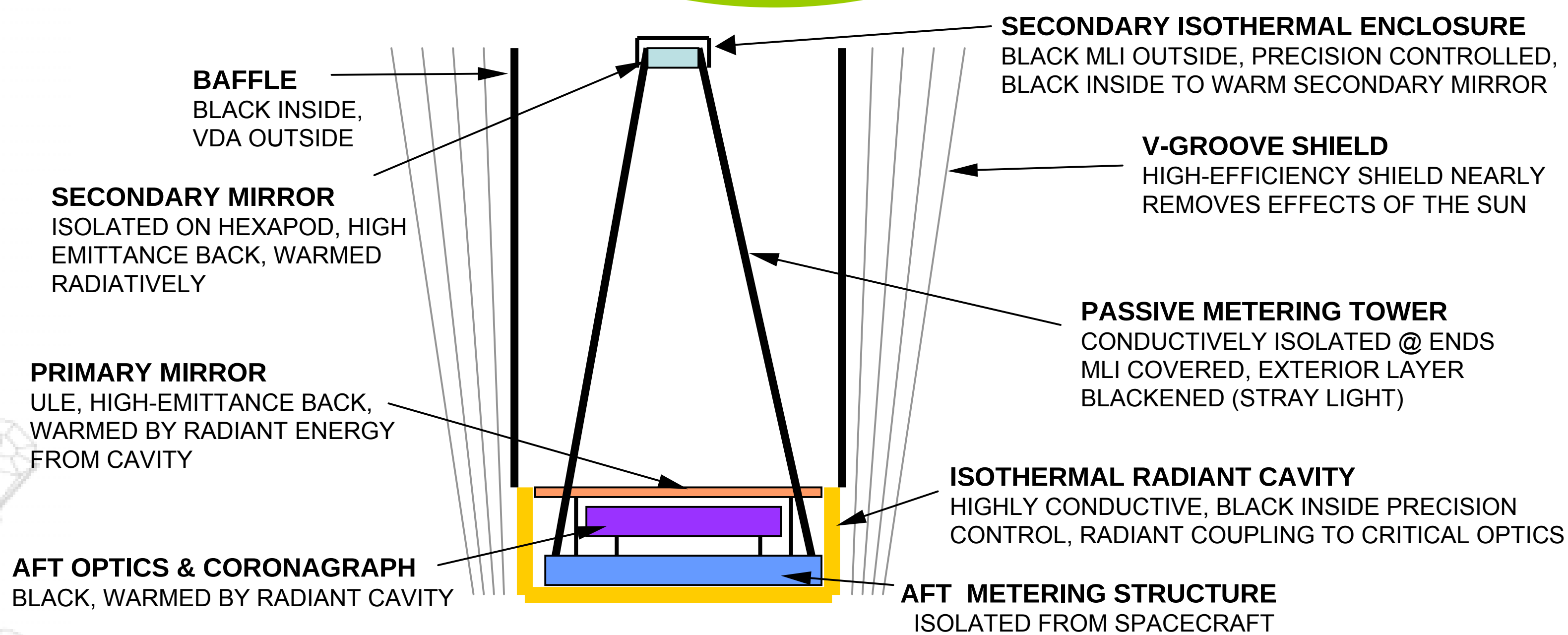
Secondary mirror radiatively maintained warm

Secondary support tower cools passively inside thermal blankets (outer layer black for stray light)

- **Passive control at depressed temperature**

Entire telescope allowed to cool to ‘equilib-rium under influence of view to cold space

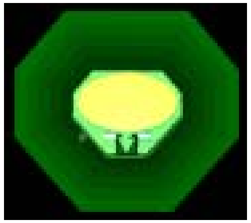
Rejected -- would prohibitively complicate ground testing



Minimum Mission Thermal Modeling

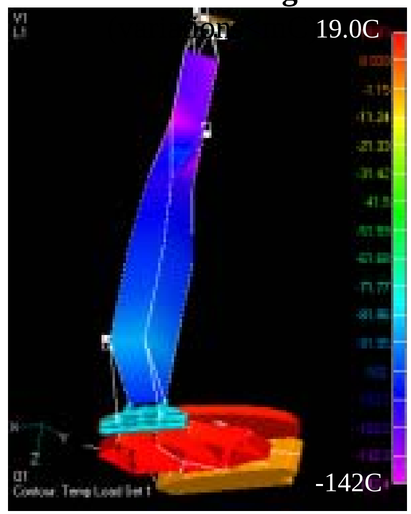
Telescope Steady-State Temperature for Two 20 deg Dither Cases (80 to 100 & 170 to 190)

170 deg **190 deg**

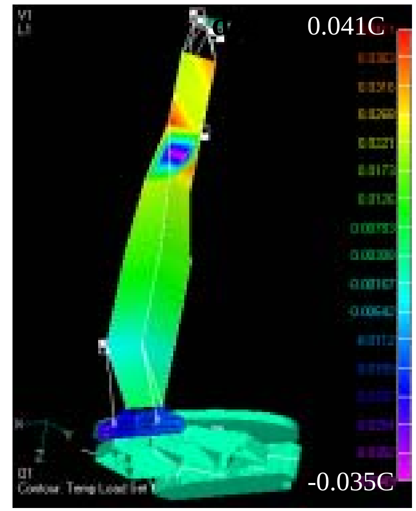


100 deg
80 deg

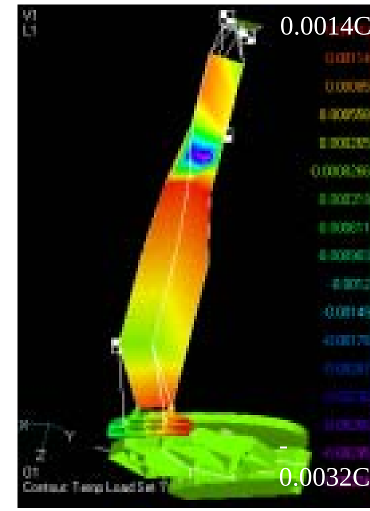
Temperature (C) Distribution for **all Sun Angles**



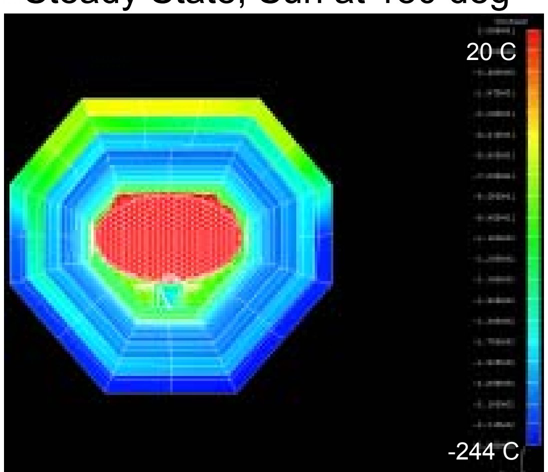
Delta Temperature (C) for Dither from **80 to 100**



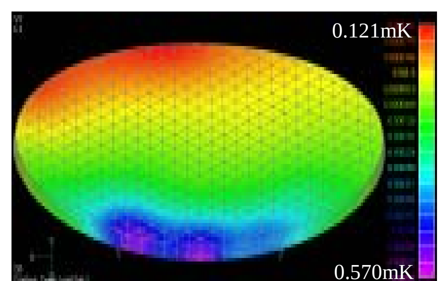
Delta Temperature (C) for Dither from **170 to 190**



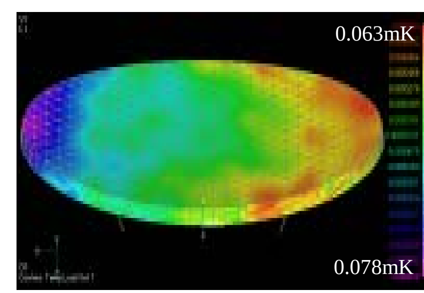
Steady State, Sun at 180 deg



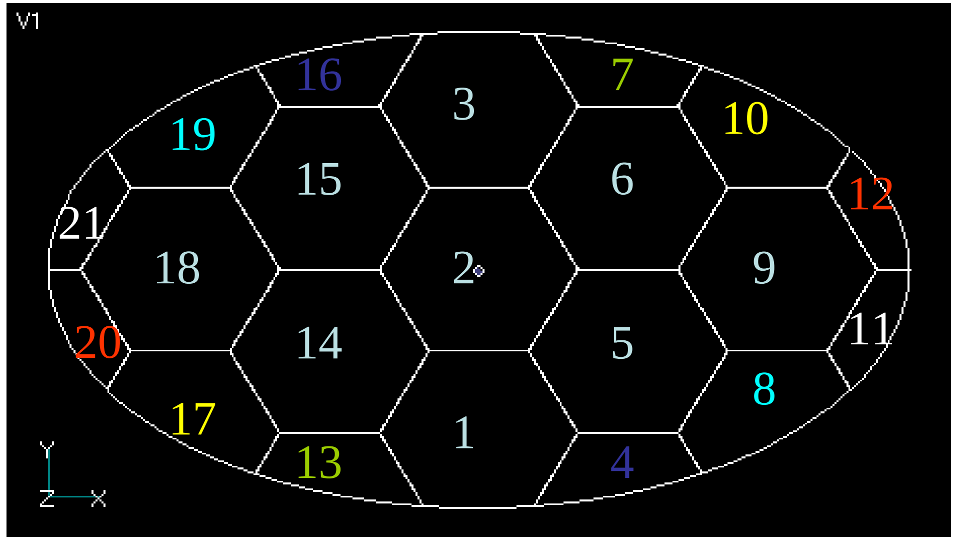
Dither from **80 to 100 deg**
Front Face Sheet of PM 0.69 mK p-v



Dither from **170 to 190 deg**
Front Face Sheet of PM 0.14 mK p-v



Thermal Modeling Results



Summary for PM Design with **Optimized** Segment Placement Based on 80 to 100 deg Dither

	80 to 100 deg Dither		
Zernike Comp	Stead-State Resp (pm)	3L/D Req Specs (pm)	Ratio Req/Resp
4	0.14	2.29	16.21
7	0.19	0.29	1.47
11	0.09	0.14	1.64
12	0.11	0.29	2.53
13	0.07	0.29	3.86

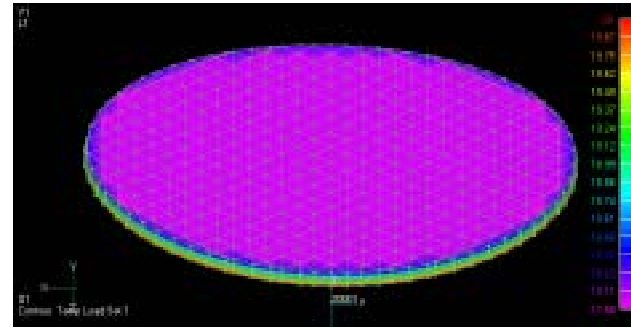
Results for 170 to 190 deg Dither Using **Optimized** Segment Placement

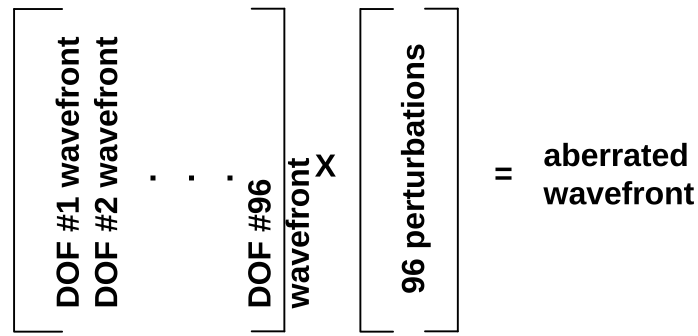
	170 to 190 deg Dither		
Zernike Comp	Stead-State Resp (pm)	3L/D Req Specs (pm)	Ratio Req/Resp
4	0.02	2.29	126.52
7	0.06	0.29	4.88
11	0.01	0.14	22.70
12	0.01	0.29	40.28
13	0.03	0.29	9.93

Note: The results for PM with optimal segment placement are **steady-state** (conservative for dither)

Integrated Optical Modeling Process

- Optical prescription converted from ZEMAX to MACOS (only one out of the four possible paths)
- Linear optical sensitivity matrices are computed using the MACOS model
  - Rigid body sensitivities
  - Flexible primary mirror sensitivities (423 nodes)
  - Rigid body sensitivities generated by perturbing each optical element, one degree of freedom at a time
    - Wavefront at the occulting mask is computed using raytracing
    - Each resulting wavefront is reshaped into a vector and becomes a column in a sensitivity matrix
    - There are 16 optical elements, resulting in 16 x 6 = 96 degrees of freedom
  - Each node on the primary mirror is given a unit displacement in the Z-direction, one at a time, and the resulting wavefront is stored as a column vector
    - Same process as for rigid body sensitivities





- The resulting wavefront is characterized by the first 15 Zernike terms, which can then be compared to requirements in the error budget
  - We have verified that the errors can be well-represented by the first 15 Zernike terms
  - Contrast results obtained by applying the perturbations directly to MACOS model
    - (plane-to-plane diffraction between each optical element).
- The error budget calculated with Fourier optics model of coronagraph
  - compute relationship between wavefront error at occulting mask and contrast
- MACOS uses full near-field diffraction model of the optical system to compute contrast

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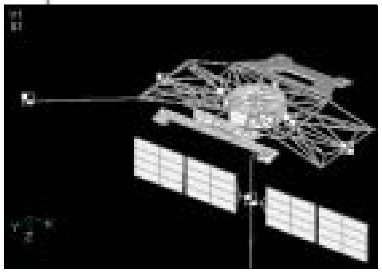
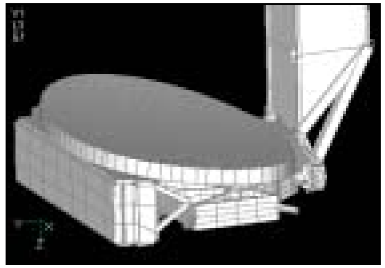
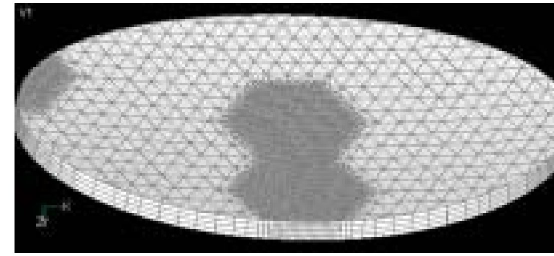
Structural and Dynamic Modeling and Analysis



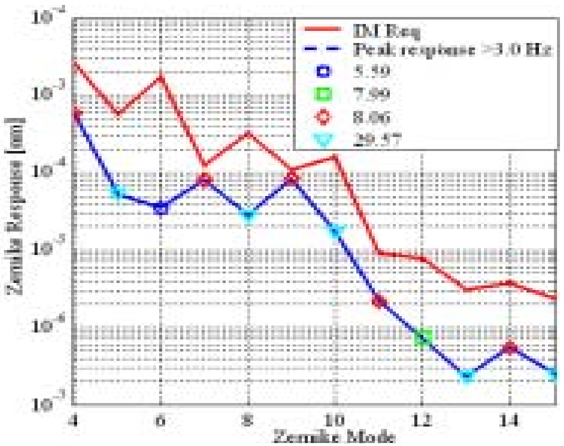




Dynamic Results - 2 stage passive isolation

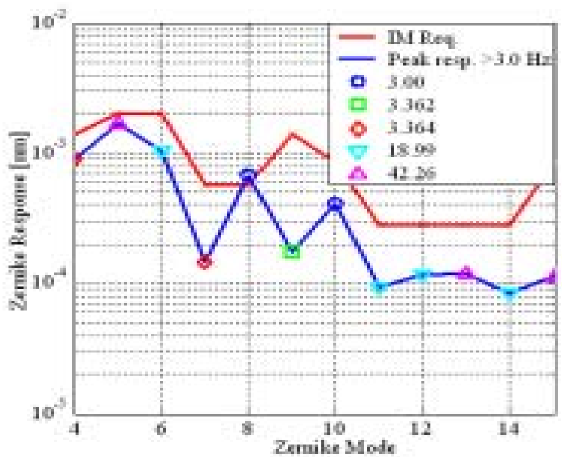
Rigid Optics Wavefront Error

Design meets requirements passively



Flexible Primary Wavefront Error

Mode 8 exceedance can be avoided by running wheels above 4hz



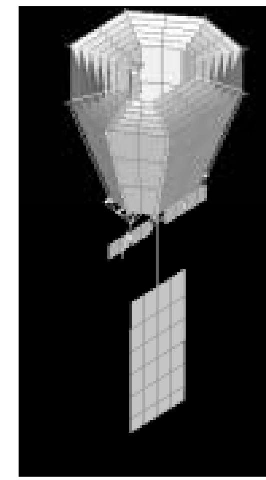
Materials Used:

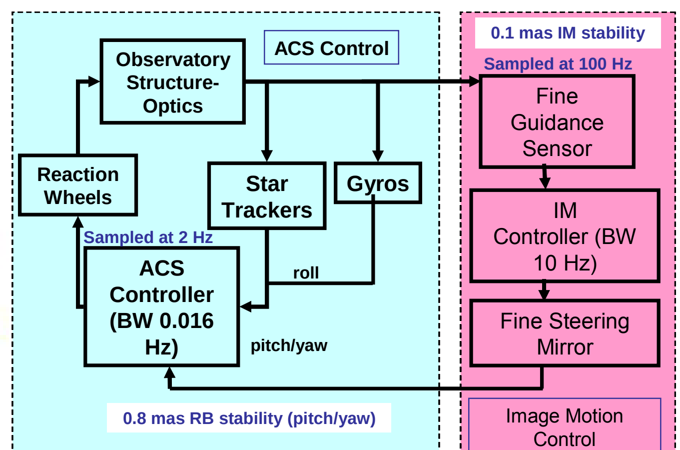
ULE Glass (Ultra-Low Expansion Titanium Silicate Glass by Corning)
- Primary & Secondary Mirrors (good thermal stability)

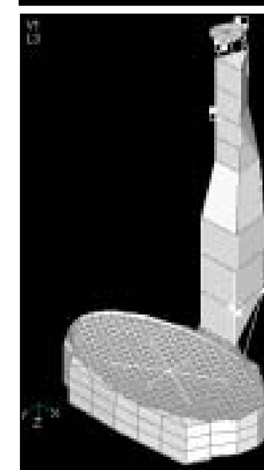
K1100/954 Carbon Fiber Composite
- Primary & Secondary Mirror Thermal Enclosures (high conductivity)

S-Glass Fiberglass Composite
- AMS/secondary tower bracket & SMA isolators, launch struts (low conductivity)

M55J/954 GrEp
- AMS, secondary tower & bracket (good thermal stability & stiffness)







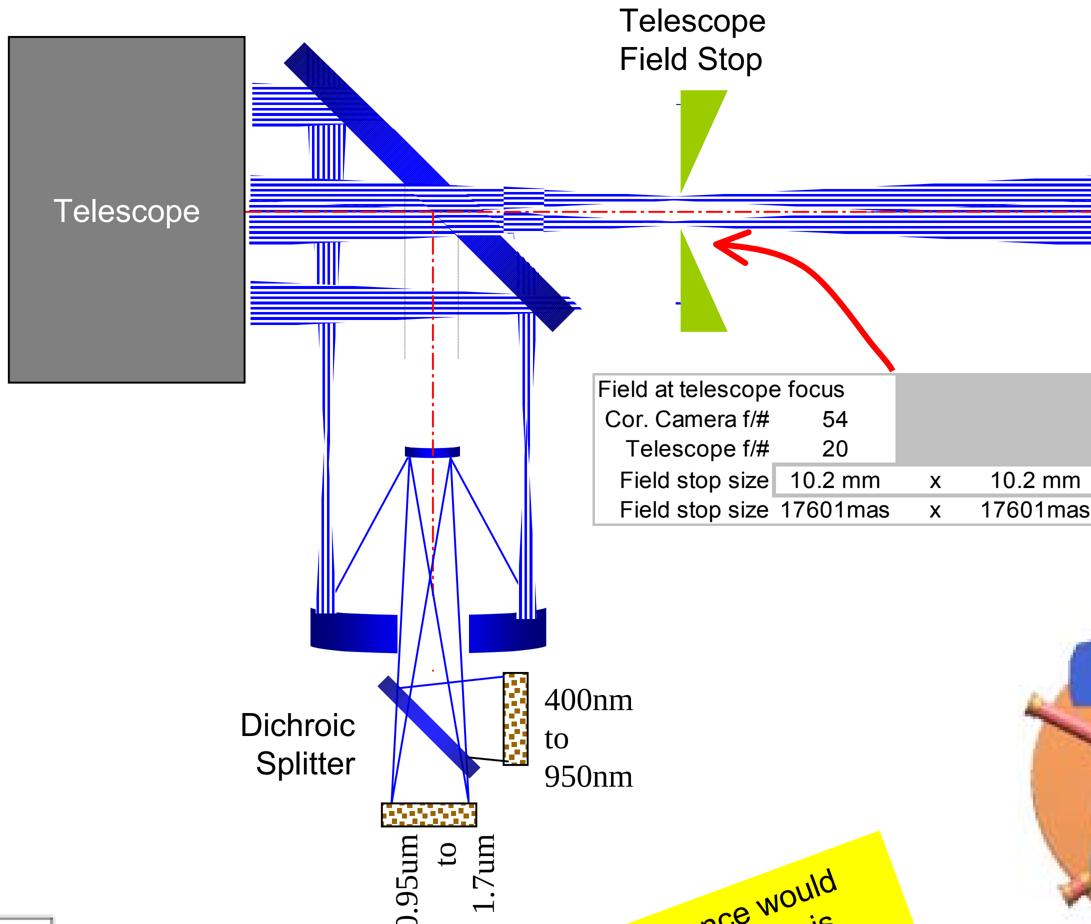
Error Budget Summary

Beam Walk Contrast due to pointing (rigid body)				
Element	**Dx**	**2λ/D**	**3λ/D**	**4λ/D**
Primary	6.30E-07	5.05E-18	1.13E-17	2.01E-17
Secondary	8.42E-09	4.44E-18	5.69E-18	5.59E-18
Fold Mirror 1	6.79E-07	1.04E-13	1.13E-13	1.02E-13
Fold Mirror 2	9.07E-07	1.86E-13	2.02E-13	1.82E-13
DM Collimator (OAP	7.89E-07	4.42E-13	3.72E-13	3.03E-13
DM	3.87E-17	1.00E-34	2.25E-34	4.00E-34
Relay OAP2	7.88E-12	4.41E-23	3.71E-23	3.02E-23
BS1	1.73E-07	4.20E-16	4.57E-16	4.13E-16
BS1	1.98E-07	8.82E-15	9.60E-15	8.66E-15
BS1	1.50E-07	3.19E-16	3.48E-16	3.14E-16
BS2	1.44E-07	2.91E-16	3.17E-16	2.86E-16
BS2	1.62E-07	3.68E-16	4.01E-16	3.62E-16
BS2	1.22E-07	2.09E-16	2.27E-16	2.05E-16
Fold Mirror 3	1.09E-07	2.69E-15	2.93E-15	2.64E-15
Michelson BS	5.28E-08	3.93E-17	4.28E-17	3.86E-17
Michelson BS	4.90E-08	5.43E-16	5.91E-16	5.33E-16
Michelson BS	2.72E-08	1.04E-17	1.14E-17	1.02E-17
Wedge 1	2.04E-08	5.88E-18	6.41E-18	5.78E-18
Wedge 1	1.69E-08	4.04E-18	4.40E-18	3.97E-18
Wedge 1	2.33E-13	7.67E-28	8.35E-28	7.54E-28
Wedge 1	2.81E-13	1.12E-27	1.22E-27	1.10E-27
Michelson BS	3.74E-13	1.98E-27	2.15E-27	1.94E-27
Michelson BS	6.91E-13	6.74E-27	7.34E-27	6.62E-27
Michelson BS	7.27E-13	7.46E-27	8.12E-27	7.32E-27
Fold Mirror 4	1.81E-12	7.37E-25	8.02E-25	7.24E-25
Relay OAP3	6.16E-12	2.70E-23	2.27E-23	1.85E-23
Relay OAP4	6.73E-12	3.22E-23	2.70E-23	2.20E-23
Reflector Flat	2.10E-11	9.95E-23	1.08E-22	9.78E-23
Occulting Mask Retu	2.82E-11	1.79E-22	1.95E-22	1.76E-22
Exit Pupil Return	1.91E-13	8.25E-27	8.99E-27	8.11E-27
TOTAL			7.02E-13	

Error Tree Terms

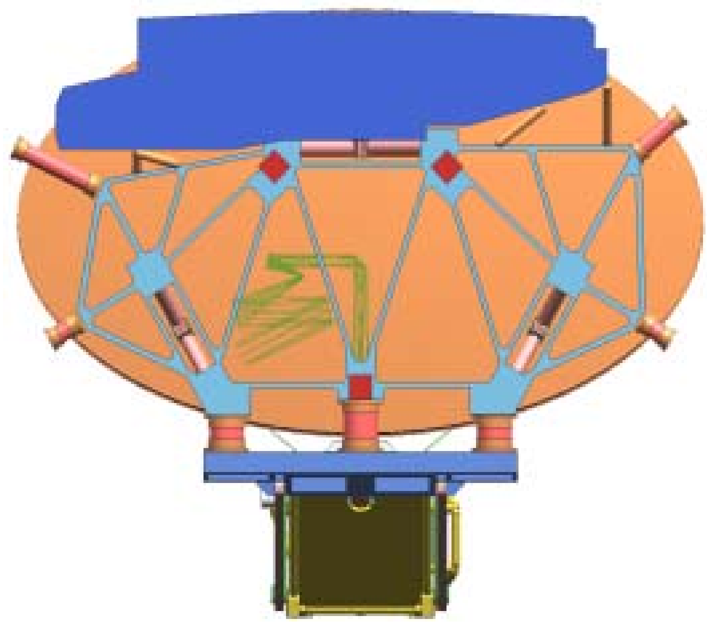
- **Mask Leakage**: image offset from the ideal on-axis position allows light to diffract past the Lyot Stop
- **Structural Deformation Beam Walk**: Tip/tilt/piston of optics causes transverse motion of the downstream beam. Motion across imperfect optics modifies the wave front and scatters light.
- **Structural Deformation Aberrations**: The system is aberration-free in its ideal state. When perturbed, aberrations result (even for perfect optics), scattering light to the image plane.
- **Deformation of Optics**: Bending of optics causes aberrations, again scattering light.
- **Rigid Body Beam Walk**: Rigid body pointing errors of the optical train up to the fast-steering mirror result in transverse beam motion.

Additional Instrument accommodations



Field at telescope focus			
Cor. Camera f/#	54		
Telescope f/#	20		
Field stop size	10.2 mm	x	10.2 mm
Field stop size	17601mas	x	17601mas

2.5arcmin FFOV, 4 mirror "Best Fit"



Both pointing and science would be done in IR channel, which is CMOS based. Bright stars could be windowed, and rapidly read-out.